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SPACE RADIOISOTOPE POWER SOURCE REQUIREMENTS UPDATE AND TECHNOLOGY STATUS

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ABSTRACT

The objectives, approach and requirements for developing a space Advanced Radioisotope Power Source (ARPS) are based on potential deep space missions. Since deep space missions have not been approved, updating requirements is a continuous parallel process based on mission design, spacecraft design, science instrument design, new spacecraft technology development and power source technology. There are two potential early missions, Europa Orbiter and Pluto/Kuiper Express, which may require space ARPS. The requirements for the power source are updated, as the power source technology becomes mature. The X2000 generic spacecraft design, the AMTEC technology progress and the advanced power source design changes the requirements for the space ARPS. The baseline mission sequence is Europa Orbiter launched in November 2003 and the Pluto Kuiper Express launched in December 2004.

The Europa and Pluto mission sequence may be switched if the technology for the Europa mission is not ready by October 2000. This paper presents the objectives, approach and latest requirements for developing ARPS and the technical status of the alkali metal thermal to electric (AMTEC) conversion technology. The high-temperature, sodium containment materials that are necessary to meet the mission requirements are also discussed. An AMTEC cell concept design with eight or nine BASE tubes to match the GPHS module thermal power is also discussed.

OBJECTIVE

The objective for the first delivery ARPS is:

Develop an advanced radioisotope power system with low cost, low mass and high efficiency to provide 150 watts of electric power after 6 years of operation and 130 watts after 10 years of operation. This advanced power system will be designed and developed to be safe.

KEY FEATURES

The first delivery ARPS must comply with the following criteria:

1) Meet a lifetime requirement of fifteen years.
2) Increase the system efficiency to greater than 15 percent
3) Reduce cost and time to fabricate and deliver flight units.
4) Use exiting general-purpose heat source (GPHS) module design.
5) Develop alkali metal thermal to electric (AMTEC) converter technology.
6) Converter technology easily scaleable down in power to 100, 50, 20 and 10 watts.

REQUIREMENTS

The requirements for potential ARPSs described by Mondt, et al, (1997) for the NASA/JPL planned Outer Planets/Solar Probe (OP/SP) Project have been updated by ongoing studies at NASA/JPL. Several launch vehicles are being considered at this time and will be selected based on cost and spacecraft mass. The baseline launch dates, power levels and mission lifetimes that are based on future planned budgets and technology readiness for the proposed OP/SP missions are summarized in the following table.

MISSION	PROPOSED LAUNCH DATE	ARPS EOM POWER &LIFETIME
Europa Orbiter or	November 2003	150We @ 6 yr.
Pluto/Kuiper Express	November 2003	130We @ 10 yr.
Pluto/Kuiper Express or	December 2004	130We @ 10 yr.
Europa Orbiter	December 2004	150We @ 6 yr.

The X2000 Engineering Model Ground Spacecraft is to be completed by the end of September 2000. The fabrication and performance testing of an electrically heated ARPS breadboard converter, 4 or 8-cell, is required by January 1999. Performance testing of an electrically heated ARPS 4 or 8-cell dynamically tested prototype converter is required by September 2000. Mass and thermal models of the ARPS are required by March 2002. The first flight units and one spare are scheduled to be delivered to the launch site by June 2003 for a November 2003 launch.

The critical ARPS requirements, in order of priority, are as follows:

Safety:	Must be safe
Cost:	Fixed within the given budget
Lifetime:	6 years for the Europa Orbiter mission
	10 years for the Pluto Kuiper Express mission
Power:	150 watts at the end of the Europa Orbiter mission
	130 watts at the end of the Pluto Kuiper Express mission
Voltage:	28 Vdc +/- 1 Vdc for each flight unit and the common spare
Mass:	20 kg or less for each mission
System Efficiency:	16% goal end of mission

ARPS FIRST DELIVERY APPROACH

Department of Energy (DOE) will do the ARPS technology development for the National Aeronautic and Space Administration (NASA). NASA Jet Propulsion Laboratory will coordinate the effort for NASA and provide the requirements to DOE for the ARPS. DOE will contract the development to a System Integrator Contractor. The ARPS System Integrator and the AMTEC Converter Subcontractor will team with NASA JPL, NASA LeRC, ORNL, Los Alamos National Lab, Mound Lab and Air Force Research Lab, Phillips Site to develop the ARPS.

The approach for developing the AMTEC technology is to select the AMTEC cell operating temperatures necessary so that the ARPS final units will meet the flight requirements. The baseline cell materials are selected that will meet the fifteen year requirement based on the operating temperatures. The selected material must be compatible with the Beta double prime Alumina Solid Electrode (BASE), the Titanium Nitride (TiN) electrodes and the Molybdenum current collectors. The materials must contain sodium vapor and be capable of wicking liquid sodium from a very low vapor pressure, ~ 10^{-4} tor, to a sodium vapor pressure of ~ 1 atmosphere. Using the selected baseline materials, the AMTEC converter contractor will fabricate AMTEC components and cells and the supporting team will conduct tests to verify predicted component and cell performance and lifetime.

In parallel with AMTEC cell development, the System Integrator and supporting team will prepare the ARPS generator concept design, preliminary design and final design using the experimental performance of the AMTEC converter technology to meet the flight unit requirements. Based on the concept design, the converter contractor will fabricate, test and deliver a breadboard converter that represents a prototypic ¼ to ½ portion of the ARPS generator for further tests to verify predicted generator thermal and electrical performance.

The converter contractor team will make changes to improve the AMTEC cell performance based on the cell and converter test results up to the preliminary design of the ARPS generator. At this point in AMTEC technology development the AMTEC cell design will be frozen so that the cell lifetime can be analytically and experimentally validated in time for the first space mission. Then the system integrator contractor team will complete the final design of the ARPS flight generator. The converter contractor will fabricate AMTEC cells and the system integrator will fabricate generator components and assemble the Qualification Unit.

The Qualification Unit will be electrically heated to validate the predicted generator performance, then environmentally tested and reheated electrically to verify no changes in performance. The Qualification Unit will then be tested as above with flight nuclear GPHS modules by BWX Technologies at Mound Lab. The ARPS's generator and AMTEC cell as built design drawing, specifications, fabrication procedures and Qualification Unit will be delivered to a flight project. This will complete the ARPS technology development.

TECHNOLOGY STATUS

The first AMTEC cell was designed to better match the heat flow from the radioisotope heat source. This cell had 6 BASE tubes connected in series inside one stainless steel sodium container as shown in Figure 1. For the long life required for space power, molybdenum was used instead of copper as current collectors. This cell designated PX-4B performed moderately well, as shown in Figure 2, when compared with the earlier technology development AMTEC series PX-1 and PX-2 cells. PX-4B had some compromises during the fabrication that reduced its power. The PX-4C AMTEC cell was identical to PX-4B, except with improvements in fabrication and the evaporator was 0.19 cm closer to the hot end. This cell performed very well with a maximum power of 5 watts with a hot side temperature of 1025K and a BASE temperature of 975K, as shown in Figure 2.

The PX-5A AMTEC cell, identical to PX-4C as shown in Figure 1, was the final technology development single cell test, as reported by Sievers, et al (1998), before the fabrication of eight identical cells for the 8-cell converter ground system. The PX-5A cell produced slightly lower power than PX-4C at the peak power point. Ten PX-G AMTEC cells were fabricated identically to PX-4C as a batch for the 8-cell converter ground system. Carlson, et al, (1998) report the results of the acceptance testing of these cells. Eight of these ten cells were installed in an AMTEC converter system and tested at the Air Force Research Laboratory, Phillips Site.

The 8-cell converter initial power output was 26 watts. The 8-cell converter operated for over 2000 hours at a power output of 25 watts with a system efficiency of 10% as shown in Figure 3. Taking into account system thermal losses and the electrical interconnect losses; the AMTEC cells operated at an average efficiency of 13 to 14%. At hot side operating temperatures of ~1100K, these early cell efficiency results are exactly what is predicted.

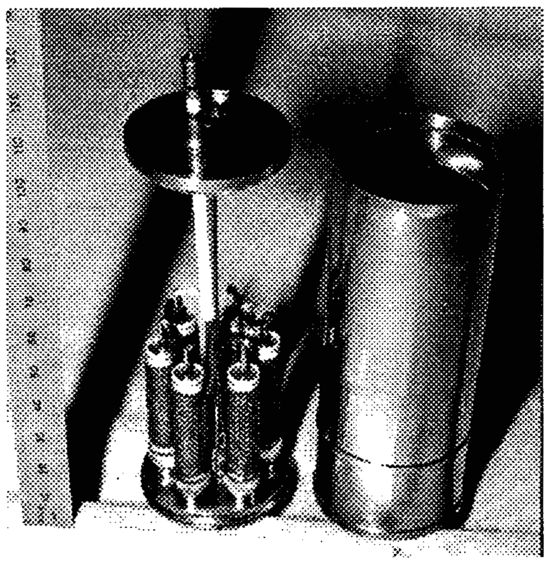

Figure 1. AMTEC Cell with 6 BASE Tubes

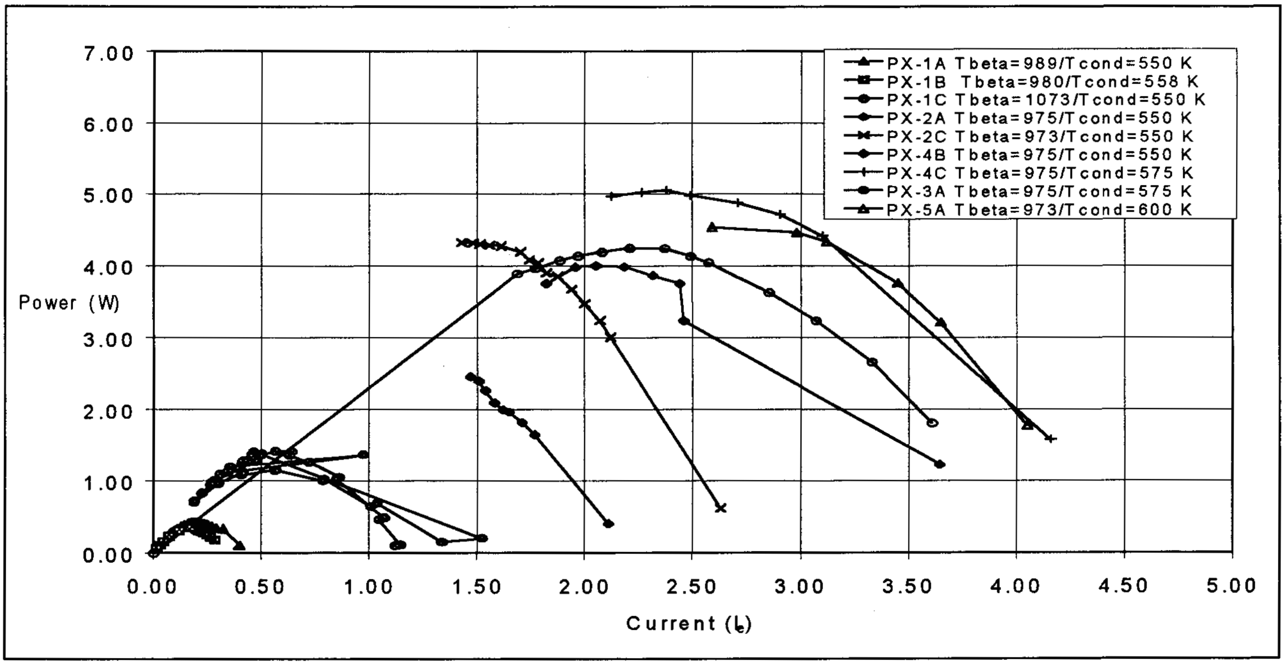

Figure 2. Measured Power (Figure provided through the courtesy of J. Merrill at Phillips Site

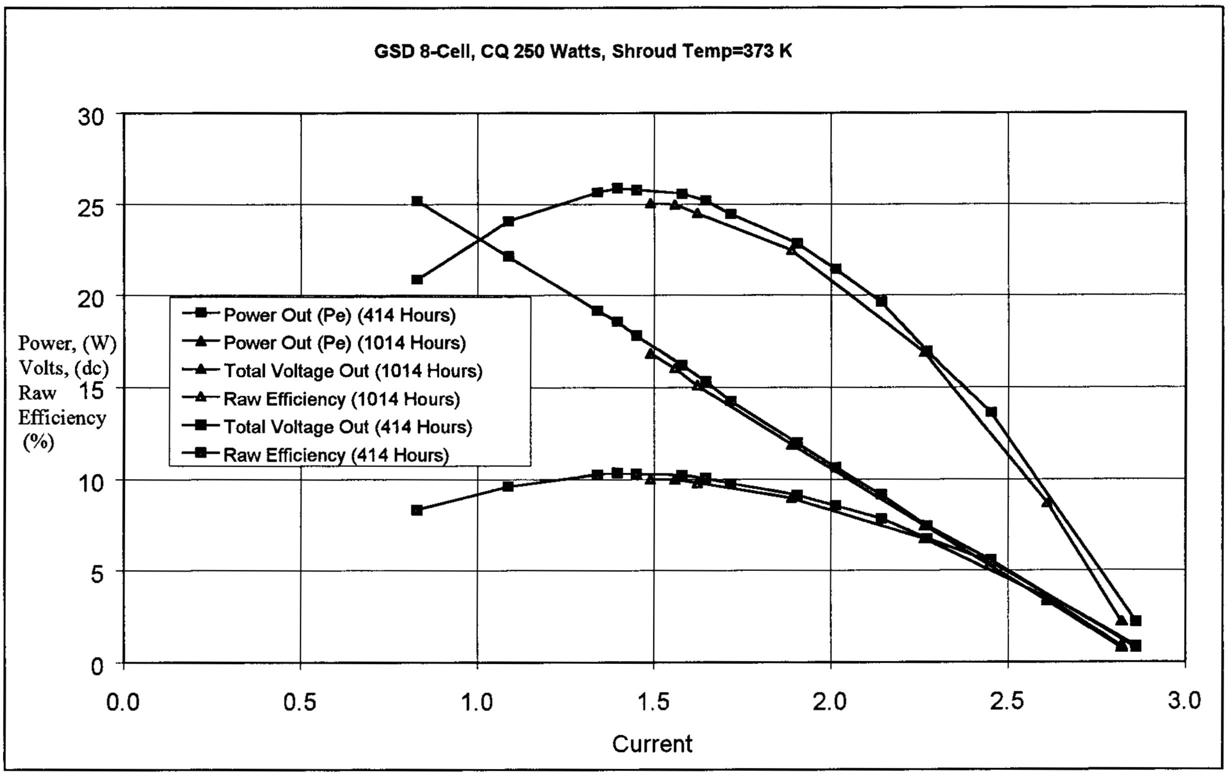

Figure 3. AMTEC 8-Cell Converter Performance (Provided by J. Merrill of Phillips Lab)

TECHNOLOGY REQUIRED

ARPS must operate at higher temperatures, higher powers and higher efficiencies than present technology to meet potential deep space mission requirements. The existing AMTEC technology uses stainless steel materials as the sodium containment material. Stainless steel limits the hot side temperature for a ten to fifteen year lifetime AMTEC cell to 925K or less. The AMTEC cell hot side temperature needs to be greater than 925K to meet the space specific power and efficiency requirements. Niobium 1%Zirconium (Nb1Zr) for the hot side and Nb1Zr or Niobium 10%Hafnium 1%Titanium (C103) or Niobium 27.5%Tantalum 11%Tungsten 1%Zriconium (FS85) for the cold side were selected as the AMTEC sodium containment materials to be investigated to replace the stainless steel.

Nb1Zr and C103 or FS85 materials incorporated into the AMTEC cell are expected to be able to operate on the hot side in a temperature range from 1150K to 1350 K and a cold side temperature range from 500K to 700K and meet the specific power, efficiency and lifetime requirements. Nb1Zr, C103 and FS85 containment materials and their interface will be evaluated as to performance, availability, fabricability, compatibility and lifetime performance with the AMTEC beta double prime alumina solid electrode, the titanium nitride (TiN) electrodes, the sodium working fluid, the molybdenum evaporator and the molybdenum current collectors. AMTEC cell components and cells will be built with the baseline containment materials and joints and tested to determine the performance as a function of temperature. Nb1Zr, C103 and FS85 materials will be tested with all the other AMTEC components to determine acceleration factors needed to predict AMTEC performance degradation and failure as a function of operating time at temperature.

Orbital Sciences Corporation designed an AMTEC cell with five 8.13 mm diameter BASE tubes in series, Schock, et al, (1997), as shown in Figure 4 to better match the general purpose heat source (GPHS) design dimensionally and thermally. The AMTEC cell with five BASE tubes can be designed with a cell out side diameter of 31.8 mm instead of 38.1 mm required for the 6 BASE tube AMTEC cell. An 8-cell arrangement with the smaller diameter cells matches the dimensions of the side of the GPHS module and more heat is forced through each BASE tube. This results in the BASE operating at a higher temperature, higher efficiency and producing more electrical power per GPHS. This may be required to meet the requirements for the ARPS flight units.

Orbital Sciences Corporation and Advanced Modular Systems, Inc have recently designed the AMTEC cell to maximize the electric power from each GPHS module at the lowest hot side temperature. This latest AMTEC cell concept design has eight or nine BASE tubes per cell and four cells per each GPHS module. This reduces by a factor of two the number of AMTEC cells per ARPS generator. This will be further evaluated as the ARPS generator design matures.

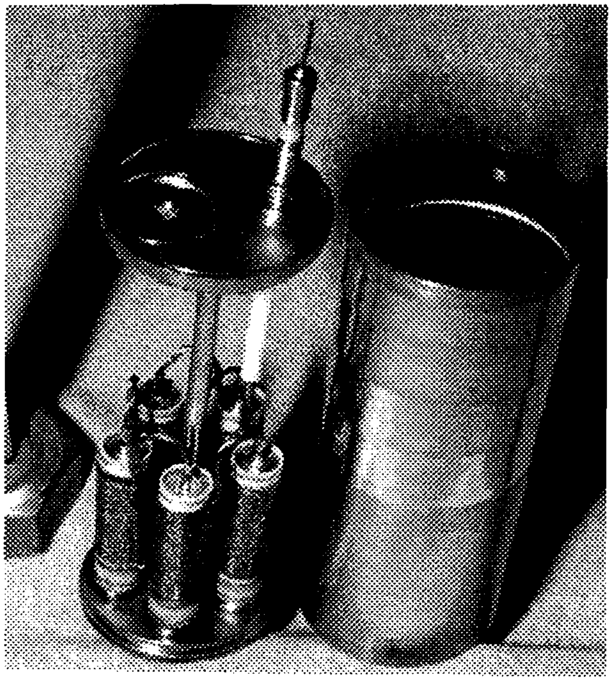

Figure 4. AMTEC Cell with 5 BASE Tubes

CONCLUSIONS

The PX series development of the Vapor-Vapor AMTEC cell was very successful as illustrated by Figure 3. In a one-year development time the power output from a multi-tube cell increased from 0.4 watts to 5 watts within the same volume. The first attempt to fabricate identical cells and test them in a prototype space configuration was also very successful. Two of the ten cells were fabricated and successfully tested. Then the next eight cells were fabricated, acceptance tested and assembled into the 8-cell ground converter system. This 8-cell converter system was shipped to Air Force Research Laboratory, Phillips Site and tested.

The initial power output at 1095K hot side temperature, with 250-watt thermal input, was 26 watts at 18 volts. However, based on the single cell tests of PX 4C and PX 5A, which produces 5 watts at 2 volts, the 8-cell in series converter was expected to produce close to ~40 watts at 16 volts. The 8 cells in the converter did not perform uniformly and there is more current collection and intercell I^2R lead losses than predicted. These are challenges that are being addressed in the ongoing technology development program. With 250 watts thermal input power the peak electrical output power degraded from 26 watts, 18 volts at 414 hours to 25 watts, 16.7 volts at 1014 hours to 24 watts, 17.1 volts at 2622 hours. The 8-cell converter was still operating when this paper was completed.

The Nb1Zr, C103 and FS85 materials and their joints are being designed, developed and tested for use in the AMTEC cells for ARPS. The new eight or nine BASE tube AMTEC cell is being designed to produce the maximum power per GPHS module in an ARPS generator configuration.

ACKNOWLEDGMENTS

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